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SMOLDERING COMBUSTION

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INTRODUCTION

Smoldering is a slow, low-temperature, flameless form of combustion, sustained by the heat evolved when oxygen directly attacks the surface of a condensed-phase fuel. Smoldering constitutes a serious fire hazard for two reasons. First, it typically yields a substantially higher conversion of a fuel to toxic compounds than does flaming (though this occurs more slowly). Second, smoldering provides a pathway to flaming that can be initiated by heat sources much too weak to directly produce a flame.

The term smoldering is sometimes inappropriately used to describe a non-flaming response of condensed-phase organic materials to an external heat flux. Any organic material, when subjected to a sufficient heat flux, will degrade, gasify, and give off smoke. There usually is little or no oxidation involved in this gasification process, and thus it is endothermic. This is more appropriately referred to as forced pyrolysis, not smoldering.

A burning cigarette is a familiar example of true smoldering combustion; it is also one of the most common initiators of smoldering in other materials, especially upholstery and bedding.¹ A cigarette also has several characteristics common to most materials that smolder. The finely divided fuel particles provide a large surface area per unit mass of fuel, which facilitates the surface attack by oxygen. The permeable nature of the aggregate of fuel particles permits oxygen transport to the reaction site by diffusion and convection. At the same time, such particle aggregates typically form fairly effective thermal insulators that help slow heat losses, permitting sustained combustion despite low heat release rates.

The physical factors that favor smoldering must be complemented by chemical factors as well. Like virtually all other cellulosic materials, tobacco in a cigarette, when degraded thermally, forms a char. A char is not a well-defined material, but typically it is considerably richer in carbon content than the original fuel; its surface area per unit mass is also enhanced. This char has a rather high heat of oxidation and is susceptible to rapid oxygen attack at moderate

temperatures (≥ 670 K). The attack of oxygen (to form mainly carbon monoxide and carbon dioxide) is facilitated not only by the enhanced surface area but also by alkali metal impurities (present in virtually all cellulosic materials derived from plants) which catalyze the oxidation process.² Char oxidation is the principal heat source in most self-sustained smolder propagation processes; the potential for smoldering combustion thus exists with any material that forms a significant amount of char during thermal decomposition. (Char oxidation is not always the only heat source and it may not be involved at all in some cases of smolder initiation.)³

Various quantitative combinations of these physical and chemical factors can produce a material that will undergo sustained smoldering in some conditions. The enormous range of factors results in materials that will only smolder when formed into fuel aggregates many meters across, at one extreme, to materials that smolder when formed into aggregates only a few tens of microns across. Unfortunately, a theory that allows for the calculation of materials and conditions that are conducive to smoldering has been developed only for certain types of smolder initiation. (See Section 2, Chapter 12.) Conditions sufficient to yield smolder initiation, especially near an external heat source, are not necessarily sufficient to assure self-sustained smolder spread away from the initiation region. The potential transition of the smolder process into flaming combustion is even less correlated with factors determining smolder initiation.

This chapter is restricted to consideration of post-initiation behavior of smoldering. There are a few models of smolder propagation in the literature but none sheds much light on any practical smolder problem. The state of modeling is reviewed elsewhere.⁴ Lacking any definitive theoretical description, this chapter is largely restricted to examining typical experimentally determined behavior. In this overview of smoldering, an attempt is made to convey some of the qualitative interplay of processes that determines overall behavior together with specific experimental results.

SELF-SUSTAINED SMOLDER PROPAGATION

The smolder initiation process is dominated by the kinetics of the oxidation of the solid. Subsequent propagation of smolder is controlled to a large degree, however, by the

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rate of oxygen transport to the reaction zone. The control via transport rate occurs because the heat evolved during smolder initiation raises the local temperature and thus the local reaction rate, until all of the neighboring oxygen is consumed. Subsequently, the reaction continues to consume oxygen as fast as it reaches the reaction zone, yielding a very low oxygen level locally, which limits the reaction rate.

The subsequent evolution of the smoldering zone away from the initiation region is heavily influenced by oxygen supply conditions. If initiation occurs deep within a layer of fine particles (sawdust, coal dust), for example, it will slowly work its way to the nearest free surface at a rate dictated by oxygen diffusion through the particle layer. (The more coarse and loosely packed the particles, the greater the influence of buoyant flow through the fuel leading to predominant upward spread.) When the smolder zone reaches the free surface region, it will spread more rapidly over this region in response to local convective and diffusive oxygen supply conditions. As will be seen, when smolder spread over the surface region of a fuel layer is forced by airflow, its response also depends on heat transfer considerations.

In examining self-sustained smolder propagation and its response to oxygen supply conditions, dimensionality is important. It is necessary to distinguish one-dimensional from multi-dimensional configurations. It is further necessary to discern whether the smolder zone is spreading in the same or opposite direction as the net movement of oxygen.

One-Dimensional Smolder Spread

One-dimensional smolder spread is an idealized situation that is sometimes approximated in real fires. For example, the spread outward or upward from deep in a layer of fuel particles approaches this one-dimensional limit when oxygen diffusion dominates convection and any curvature of the reaction front is small compared to the reaction zone thickness. In practice, this curvature requirement would likely be met by spread about 0.10 to 0.20 m away from the ignition source. One-dimensional smolder can be characterized by the direction of smolder propagation relative to the direction of oxygen flow: forward and reverse propagation.

Reverse propagation: When oxygen diffuses to the reaction zone from the outer surface of the fuel layer, through the unburned fuel and toward the reaction front, it is moving opposite to the direction of smolder propagation; such a case of relative movement is called reverse smolder.

Palmer⁵ examined this diffusive reverse smolder case using layers of wood sawdust of various depths; the configuration was only roughly one-dimensional. Some of his results are shown in Figure 2-11.1. Note that the time scale is in hours; the time to smolder up through a layer 1 m deep is about two weeks, a surprisingly long time. Palmer noted that in this configuration the smoldering process gave little hint of its presence until it was close to the surface of the fuel layer.

The slope in Figure 2-11.1 indicates that the time for smolder to penetrate a fuel layer in this mode is nearly proportional to the square of the layer depth.⁵ Palmer showed that a second power dependence on layer depth would be expected if it is assumed that the smolder reaction zone propagation velocity is proportional to the one-dimensional diffusion rate of oxygen from the surroundings, through the unburned fuel, to the reaction zone. This results in

$$t_L = AL^2 \quad (1)$$

where t_L is the time for the smolder zone to penetrate the layer of thickness, L ; and A is a constant that can, at present, only be determined by experimental measurement of at least one layer thickness.

This relation and Figure 2-11.1 imply that a 10-m fuel layer, such as might be encountered in a landfill or coal mine tailing pile, would require more than four years for smolder penetration. Such a deep layer is unlikely to be uniform in practice and the smolder front movement would be dominated by buoyant convective flow in regions of lesser flow resistance. However, this does illustrate how very slow some smolder processes can be.

A well-insulated reaction zone is a key factor in the existence of stable, self-sustaining smolder at such extremely low rates. The heat loss rate cannot exceed the heat

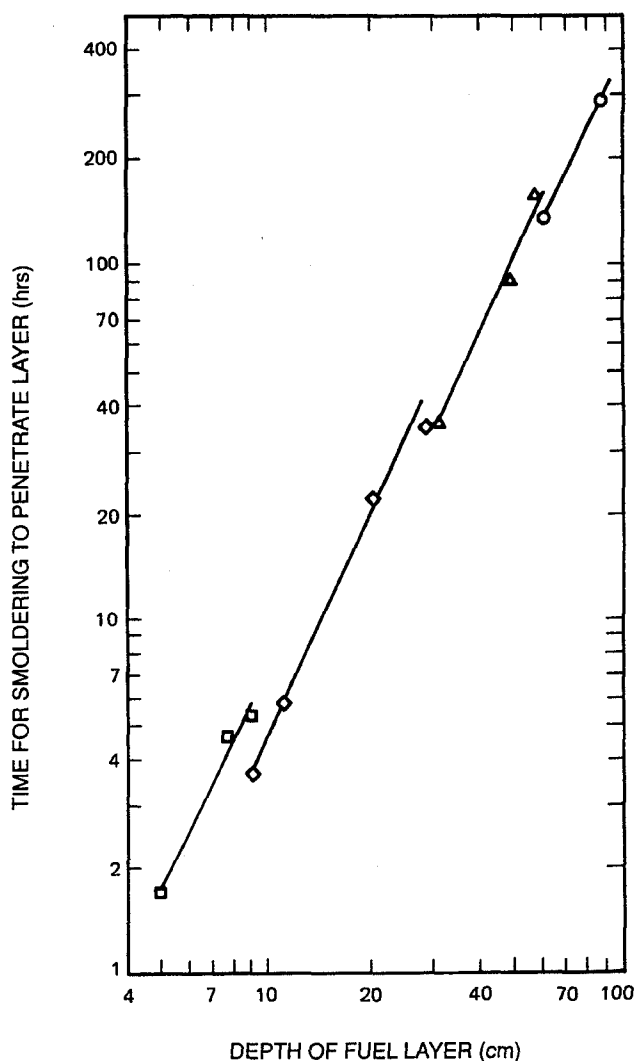


Fig. 2-11.1. Smoldering upward from bottom within thick layers of mixed wood sawdust.⁵ Squares: initiating layer 0.025 m deep, 0.3 m square box; diamonds: initiating layer 0.052 m deep, 0.3 m square box; triangles: initiation layer 0.052 m deep, 0.6 m square box; circles: initiating layer 0.052 m deep, 0.9 m square box.

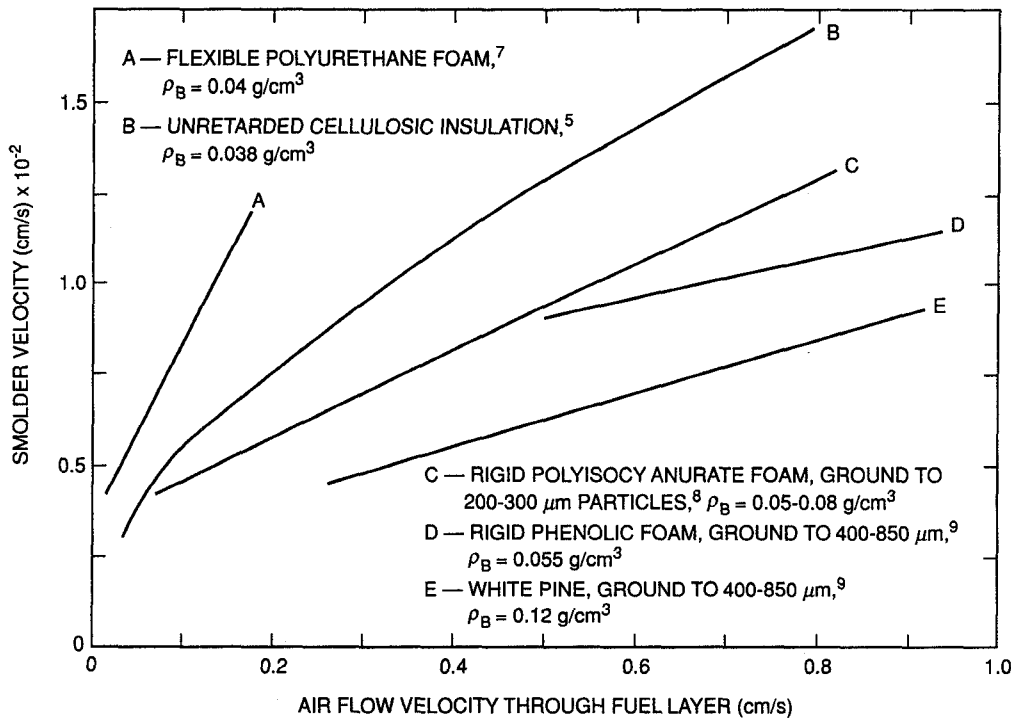


Fig. 2-11.2. Smolder velocity vs airflow velocity into reaction zone for nearly one-dimensional reverse smolder. ρ_B is bulk density.

generation rate. In this case, the same factor that is slowing the oxygen supply rate, and therefore the heat generation rate (i.e., the thick layer of wood particles over the reaction zone), is also slowing the heat loss rate.

In the previous example, the smolder propagation process is inherently unsteady because of the time-dependent oxygen supply process. If oxygen is instead continually supplied by a forced convective flow through the fuel layer, nearly steady propagation occurs. Such a configuration is encountered in some incinerators and coal burners but rarely in a smoldering fire. This configuration has been examined experimentally⁶ and modeled,^{7,8} and is a relatively well-understood smolder mode with underlying mechanisms qualitatively similar to the transient case just discussed.

In this mode of reverse smolder propagation, oxygen surrounds the fuel particles as they are heated by the advancing smolder reaction zone. Thermal degradation of some fuels in the presence of oxygen is exothermic. This is particularly true of cellulosic materials and this heat can be sufficient to drive the smolder wave without any char oxidation.⁶ In flexible polyurethane foams, the presence of oxygen during degradation plays another key role. Without oxygen many foams do not form any char,⁷ although char oxidation is a necessary source of heat for these materials. In the reverse smolder mode, the net oxidation rate and net heat release rate are again directly proportional to the oxygen supply rate; the smolder zone spreads to adjacent material as fast as this generated heat can be conducted and radiated to it. An increased oxygen supply rate causes a greater rate of heat release and increased peak temperature in the reaction zone which, in turn, increases the heat transfer rate to adjacent fuel, thus accelerating the smolder spread rate. This sequence implies that the smolder reaction zone may well move through a layer of fuel without fully consuming the solid at any point. This unconsumed material,

in fact, acts like an insulator for the reaction zone, increasing its stability. On the other hand, Dosanjh *et al.*,⁸ point out that this mode of smolder propagation can achieve a steady-state only if, as a minimum, the energy released is sufficient to heat the incoming air supply; otherwise it will extinguish.

Figure 2-11.2 shows measured reverse smolder velocities for several types of fuel as a function of airflow velocity through the fuel bed. The bulk densities of the fuel bed are all low but typical for these types of materials. Note that the airflow velocity range is also quite low, although higher flows are sufficient to move the fuel particles in the bed (i.e., an upward flow higher than approximately 0.01 to 0.02 m/s would fluidize the fuel bed).

Despite the considerable variation in the chemical nature of these fuels, the smolder velocity is always of order 10^{-4} m/s. For the same air supply rate, the smolder velocities do not vary much more than a factor of 2. This is consistent with the idea that the oxygen supply rate, not reaction kinetics, dominates the propagation process. The differences with fuel nature that do exist mainly appear to reflect variations in available heat and effective thermal conductivity.

Only limited information is available on toxic gas production from this mode of smoldering. The molar percentage of carbon monoxide in the evolved gases has been examined for two of the fuels in Figure 2-11.2. For the flexible polyurethane foam, the carbon monoxide is 6 to 7 percent for an air velocity of 1.5×10^{-3} m/s; the flow rate dependency was not examined.⁹ For the cellulosic insulation material,¹⁰ the carbon monoxide mole fraction varies from about 10 to 22 percent from the lowest to the highest air flow velocity in Figure 2-11.2. The mass flux of carbon monoxide from such a smoldering process (grams of CO/m² of smolder front/second) then is estimated as follows

$$Y_{co}(\dot{m}_{air} + \dot{m}_{GS}) \quad (2)$$

or

$$Y_{co}[\rho_{air}v_{air} + (1 - \phi)\Delta\rho_s v_s] \quad (3)$$

Here Y_{CO} is the mass fraction of carbon monoxide in the evolved product gases (approximately equal to the mole fraction); \dot{m}_{air} is the mass flux of air entering the smolder zone; \dot{m}_{GS} is the mass flux of gaseous material evolved from the solid fuel; ρ_{air} is the density of the air at the point where its velocity, v_{air} , is measured; ϕ is the initial void fraction of the fuel bed; $\Delta\rho_s$ is the change in density of the fuel bed (for reverse smolder, typically 65 to 95 percent of the original mass is gasified); and v_s is the smolder front velocity.

Limited information is also available on the aerosol emitted by a reverse smolder source;¹¹ this is pertinent to detection of a smoldering fire. The source studied was essentially identical to that used to obtain the data for curve B in Figure 2-11.2; the fuel again was an unretarded cellulosic insulation. The mass mean particle size of the aerosol was 2 to 3 μm ; this is about 5 times larger than cigarette smoke and 50 to 200 times larger than the sooty particulate produced by flaming combustion. This large size explains the relatively poor sensitivity of ionization smoke detectors to realistic smolder sources. The residual solid left in the smolder wave and the original fuel both were found to be effective filters for this aerosol; this helps explain the observation by Palmer⁵ that smoldering in a thick layer of fuel was not detectable until it neared the surface exposed to the ambient atmosphere.

The rate of heat release for this mode of smolder can be estimated from the total mass flux of products and their heat content (gas temperature typically 670 to 970 K). The result is a few kW/m^2 of smolder front. This translates to a few hundredths of a kW for a reverse smolder source 0.1 to 0.15 m in diameter. The strength of the heat source has a bearing on the behavior of the buoyant plume. (See Section 2, Chapter 2.) Sources as weak as those considered here generate plumes that may not reach the ceiling of a room.¹²

Forward propagation: The second limiting case of one-dimensional smolder propagation is called forward smolder; in this case the oxygen flow is in the same direction as the movement of the smolder front. The most familiar example (though not one-dimensional) of forward propagation is a cigarette during a draw. This limiting case is encountered in some industrial combustion processes but is unlikely to be found in its pure, one-dimensional form in a fire context (some elements of this mode are encountered in realistic cases, however). An approximate model of this process (in one dimension) has been presented by Dosanjh and Pagni.¹³ They point out that this smolder mode will die out if the heat generated by char oxidation is insufficient to drive the drying and fuel pyrolysis reactions that precede char formation in the reaction zone.

Some characteristics of forward propagation are briefly mentioned here to describe the major effects that reversing the direction of oxygen flow can have on smolder propagation characteristics.

Forward and reverse smolder propagation have been compared experimentally;^{6,10} the fuel was an unretarded cellulosic insulation. Forward smolder through this same fuel at the same air supply rate is about ten times slower than reverse smolder. The carbon monoxide mole fraction is independent of air supply rate and is about 9 percent. Forward

smolder also allows for more complete combustion of the fuel. These and other differences between the two smolder modes can be explained in terms of the differing wave structures.⁶

Frandsen¹⁴ investigated the downward propagation of smoldering in horizontal layers of peat as a model fuel for the complex duff layer found on the floor of a forest. No external flow was imposed. This is essentially a diffusion-driven forward smolder process forced to be one-dimensional in this study; it normally is multidimensional in character. The influence of both moisture and inorganic diluents on the limits of smolder propagation was measured. At the extremes, it was found that this cellulosic fuel will just smolder when it contains 50 percent water by weight and no inorganic diluents; when dry it will just smolder when the mix contains 80 percent inorganic diluents. These results should be roughly indicative of the limits for other cellulosic fuels in the absence of a crossflow over the fuel layer.

Multi-Dimensional Smolder Spread

Factors such as ignition source geometry, fuel geometry, and the strong influence of buoyant flow on oxygen supply usually interact to assure that a smolder reaction zone has significant gradients of temperature and species in two or three dimensions. The number of possible configurations becomes virtually limitless. The practical configurations that have been studied are few and they are usually two-dimensional; they do shed some light on most cases likely to be of interest.

Horizontal fuel layer: The configuration that has been studied most extensively is two-dimensional smolder propagation in a uniform horizontal layer of particles or fibers. Ohlemiller¹⁵ examined the structure of the smolder zone in a thick (0.18-m) horizontal layer of cellulosic insulation in the absence of any forced airflow over the fuel layer. In these conditions, the flow induced by the buoyant plume rising above the smolder zone assures a constant supply of oxygen to the space above the layer; oxygen penetrates the layer largely by diffusion.

If such a layer is ignited uniformly on one end, the smolder reaction zone soon evolves into a new shape dictated by oxygen supply rates.¹⁵ The uppermost elements of the reaction zone, being closest to the free surface and hence, ambient air, spread away from the ignition source the fastest; successively deeper elements spread in the same direction but more slowly. The result is a smolder reaction zone that (viewed in vertical cross-section) slopes upward from the bottom of the layer to the top, in the direction of movement. The steady-state length of this inclined smolder front is roughly twice the depth of the original fuel layer. This inclined reaction zone is several centimeters thick, and across this thickness there is a smooth transition from unburned fuel to ash. On the ash side (the free surface adjacent to air) oxygen diffuses down and inward in the same direction as the smolder front is moving and attacks the charred fuel; this is analogous to forward smolder discussed earlier. On the unburned fuel side of the inclined smolder front, oxygen diffuses in from the region ahead of the front to react with the fuel as it is thermally degraded by heat conducted from the char oxidation region. Oxygen here is moving opposite to the direction of smolder propagation, so this aspect of the overall reaction zone is analogous to reverse smolder. Remember that in cellulosic materials, this oxidative/thermal degradation is exothermic. Thus the two-dimensional

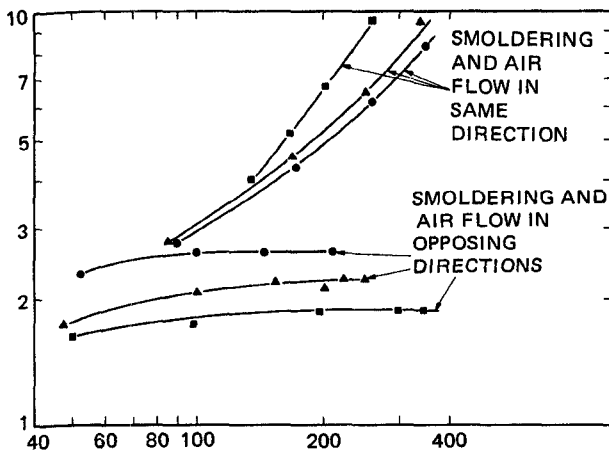


Fig. 2-11.3. Dependence of smolder propagation rate through horizontal layers of beech sawdust on air velocity over top of layer.⁴ Circles: 120 μm mean particle size; triangles: 190 μm mean particle size; squares: 480 μm mean particle size.

horizontal smolder zone incorporates features of both forward and reverse smolder and is driven forward by the combined heat release from char oxidation and oxidative/thermal degradation.

The participation of oxidative/thermal degradation in driving the smolder process requires that oxygen have free access to the thermal degradation region. For a low-permeability fuel such as solid wood, this is not the case. Even though solid wood has basically the same reaction chemistry as cellulosic insulation (which consists mostly of wood fibers) and smolders with a qualitatively similar inclined reaction zone, it must be driven solely by char oxidation.

The low permeability and corresponding high density of solid wood has another consequence with regard to smolder. The self-insulating quality of the reaction zone is much less than with a low-density layer of fuel particles or fibers. A single layer of wood will not sustain smolder unless it is subjected to an additional heat input of about 10 kW/m^2 ;¹⁶ this heat could come from some external radiant source or from another piece of smoldering wood that has an adequate radiative view factor with respect to the first piece.

In view of the strong role of oxygen supply rate in shaping the smolder process in a horizontal fuel layer, it is not surprising that smolder also accelerates in response to an increased oxygen supply rate produced by an airflow over the top of the smoldering layer. As with the one-dimensional propagation situation, two possibilities again exist: the airflow can travel in the same direction as the smolder front (again called forward smolder) or in the opposite direction (reverse smolder). Note, however, that now the actual fluxes of oxygen *within* the smoldering fuel bed may go in various directions; they are no longer constrained to being parallel to the smolder wave movement, as in the one-dimensional cases.

Palmer⁵ examined both of the flow direction possibilities for relatively thin horizontal layers (3×10^{-3} to $5.7 \times 10^{-2} \text{ m}$) of various cellulosic particles (cork, pine, beech, grass). Figure 2-11.3 shows some typical results. Note that the smolder velocities are less than or equal to those in Figure 2-11.2, despite the much higher air velocities. This is probably due to differing rates of actual oxygen delivery to the reaction zone, and to the fact that the near-surface re-

gion, which receives the best oxygen supply, is also subjected to the highest heat losses.

The influence of two factors, fuel particle size and relative direction of airflow and smolder propagation is shown in Figure 2-11.3. Particle size has a relatively weak effect on smolder velocity but its effect depends on whether the smolder configuration is forward or reverse. The configuration itself has a much greater effect.

Ohlemiller¹⁷ obtained comparable smolder velocities and dependence on configuration for 0.10- to 0.11-m thick layers of cellulosic insulation. It was found that the configuration dependence cannot be explained solely on the basis of oxygen supply rates. The mass transfer rate to the surface of the fuel bed was measured for forward and reverse configurations; it differs by only 20 to 30 percent (these differences are caused by changes in the bed shape due to shrinkage during smolder). It was pointed out that the observed dependence on relative direction of the airflow is consistent with there being a prominent role for convective heat transfer along the top surface of the fuel layer. This dependence occurs only if part of the smolder wave, i.e., the region near the leading edge, is kinetically limited (and therefore highly temperature sensitive) rather than oxygen supply rate limited. This explains the qualitative impact of both relative airflow direction and combustion retardants on smolder velocity; it also explains why forward smolder is faster than reverse smolder in the horizontal layer configuration, whereas the opposite was true for one-dimensional propagation. The role played by fuel particle size may be implicit in this view, but a quantitative model is not yet available.

In contrast to the monotonic enhancement of forward smolder velocity with increased airflow rate found by Palmer and by Ohlemiller, Sato and Segal¹⁸ observed more complex behavior with thin (0.004 to 0.01-m) layers of a cellulosic mixture. Smolder velocity increased up to freestream air velocities of about 3 m/s and then remained constant to the highest air velocity examined (6 m/s). This plateau correlated with erratic behavior at the leading edge of the smolder reaction zone involving both periodic extinctions and mechanical disruptions. These authors also examined the thermal structure of their forced smolder waves. The results were qualitatively similar to those of Ohlemiller for buoyant smolder,¹⁵ but the peak temperatures were appreciably higher due to the enhanced oxygen supply rates.

There is a minimum thickness below which a horizontal fuel layer will not undergo self-sustained smolder propagation. As the thickness of a fuel layer decreases, its surface-to-volume ratio increases (inversely with thickness to the first power). The ratio of the rate of heat loss to the rate of heat generation also varies in this manner so that ultimately the losses are overwhelming and extinction occurs. The exact thickness will depend on factors such as bulk density, fuel type and particle size, rate of oxygen supply, etc., influencing the heat generation per unit volume at a given thickness. The same considerations apply to other thin layers of fuel such as fabrics on upholstery and sheets of paper, wood, or particle board. Palmer⁵ found that the minimum depth for sustained smolder in still air increased linearly with particle size for beech, pine and cork; for cork this dependence ceased above 2 mm, apparently because more complete oxidation of the char stabilized the process in the layers of larger particles. For very small particles, ($< 100 \mu\text{m}$), the minimum depth dropped as low as 1 mm for cork dust; 0.01 m was typical of small particles of beech or pine sawdust. Ohlemiller and Rogers¹⁹ found the minimum depth in still

TABLE 2-11.1 Data on Multi-Dimensional Smolder in Various Fuels

Fuel	Fuel/Smolder Configuration	Air Supply Condition/Rate	Smolder Velocity (cm/sec)	Maximum Temp. (°C)	Ref. No.	Comment
Pressed fiber insulation board, 0.23–0.29 g/cc	1.3 cm thick, horizontal strips, width large compared to thickness	Natural convection/diffusion	$1.3\text{--}2.2 \cdot 10^{-3}$	NA	4	Smolder velocity increased $\approx 50\%$ for strips with width \approx thickness
Pressed fiber insulation board, 0.23–0.29 g/cc	1.3 cm \times 1.3 cm strips varied angle to vertical	Natural convection/diffusion	$2.7\text{--}4.7 \cdot 10^{-3}$	NA	4	Smolder velocity highest for upward spread; lowest for horizontal spread
Pressed fiber insulation board, 0.23–0.29 g/cc	1.3 cm \times 5 cm strips forward smolder	Forced flow, 20 to 1500 cm/s	$3.5 \cdot 10^{-3}$ cm/s (20 cm/s air) $13.0 \cdot 10^{-3}$ cm/s (1400 cm/s air)	770°C (200 cm/s) 790°C (900 cm/s)	4	Some samples extinguished due to air cooling at air velocity > 1450 cm/s
Pressed fiber insulation board, 0.23–0.29 g/cc	1.3 cm \times 5 cm strips reverse smolder	Forced flow, 80–700 cm/s	$2.8\text{--}3.5 \cdot 10^{-3}$ cm/s	NA	4	Extinguishment indicated above 900 cm/s
Pressed fiberboard (pine or aspen) 0.24 g/cc	1.3 cm \times 30 cm sheets, horizontal, forward smolder	Forced flow, 10–18 cm/s	$0.7 \cdot 10^{-3}$ cm/s	NA	28	
Cardboard	Vertical rolled cardboard cylinder, downward propagation, varied dia. 0.19–0.38 cm	Natural convection, diffusion	$5.0\text{--}8.4 \cdot 10^{-3}$ cm/s	NA	29	Small dia. $\approx 2 \times$ faster than large dia.; ambient temp. effect measured
Shredded tobacco	0.8 cm dia. cigarette, horizontal, in open air	Natural convection, diffusion	$3.0\text{--}5.0 \cdot 10^{-3}$ cm/s	820°C	30	
Cellulose fabric + 3% NaCl	Double fabric layer, 0.2 cm thick, horizontal, forward smolder	Forced flow, ≈ 10 cm/s	$\approx 1.0 \cdot 10^{-2}$ cm/s	770°C	31	Smolder behavior dependent on alkali metal content
Cellulosic fabric on substrates	Various weight fabrics horizontal on fiberglass, PU foam, cotton batting	Natural convection, diffusion	$\approx 3.0\text{--}75 \cdot 10^{-3}$ cm/s dependent on substrate and fabric	Reported values suspiciously low	32, 33	Smolder fastest on inert fiberglass substrate

air for an unretarded cellulosic insulation to be 0.035 m; a heavy loading of the smolder retardant boric acid roughly doubled this value. Since the insulation has a very small effective particle size and essentially the same chemistry as Palmer's sawdusts, most of the difference in minimum depth (for the unretarded material) probably lies in the bulk density, which is about four to five times less for the insulation compared to the sawdusts (40 kg/m^3 vs 180 kg/m^3). Palmer found that the minimum depth dropped rapidly with increased airflow over the sawdust layers, in keeping with the idea that a greater rate of heat release per unit volume stabilizes the smolder process.

Beever^{20,21} has addressed a problem at the opposite extreme of layer thickness, that of underground fires in landfills, peat deposits, and mine tailings. These tend to be smoldering fires in roughly horizontal layers where the principal mode of oxygen access is from the top surface. Beever²¹ studied this process on a laboratory scale using mixtures of fine sawdust or charcoal with an inert diluent, i.e., diatomaceous earth, in a trough that was insulated on the sides and bottom but open to quiescent air on the top. The trough was 0.13 m by 0.38 m in cross section and 0.14 m deep; a deeper trough was used in separate experiments in which pure layers of the inert diluent were placed atop the combustible layer. Local ignition near the top of a layer yielded steady propagation over a limited depth at rates that varied only weakly with inert content. However, while 25 percent fuel

content yielded smolder spread, 10 percent fuel content did not. The depth to which this spreading smolder zone reached increased with the cross-sectional dimensions of the fuel bed. Material below this depth, having been heated and partially decomposed by the smoldering zone above, could itself subsequently propagate a second wave moving in the opposite direction. It was pointed out that such behavior can make it possible for a landfill or similar fire to spread under a barrier intended to stop it. Similarly, inert covering layers may simply slow but not stop such fires. The true key to stopping a smoldering fire is getting the heat out of the fuel, but this can prove to be extraordinarily difficult.

Smolder propagation data on a few other fuels (including some that are inorganic) in horizontal layers can be found.¹⁹ Unfortunately, no data are currently available on the evolved products of horizontal layer smolder. For crude estimates on cellulosic materials the previous results for reverse smolder are adequate, but they should be applied here with caution.

Other fuel configurations: Data on a few other multidimensional smolder configurations are summarized in Table 2-11.1. Again there is little more information available than the rate of smolder propagation. An exception to this is the smoldering cigarette, which has been extensively studied,^{22,23,24} albeit usually in a manner most pertinent to its peculiar mode of cyclicly forced air supply.

All the materials in Table 2-11.1 are fairly porous. As noted previously, solid wood, a low-porosity fuel, also smolders, given a configuration that limits heat losses.²⁵

Ohlemiller and Shaub²⁶ and Ohlemiller²⁷ examined smolder spread along the interior surface of a three-sided channel constructed of either white pine or red oak. A controlled flow of air was introduced at one end of the channel; the products evolved from the other end were monitored as was the rate of smolder spread. For both types of wood, stable smolder was observed for only a narrow range of inlet air velocities, 0.05 to 0.20 m/s. (From limited data this appeared true for both forward and reverse smolder.) Below this range the smolder process extinguished and above it flaming eventually erupted. Both of these limits, but particularly the lower limit, are probably dependent on the specific conditions of the tests. Carbon monoxide typically comprised 2 to 3 percent of the gases leaving the channel or about 10 to 15 percent of the gases leaving the surface of the wood. The rate of heat release during smoldering was estimated from the oxygen consumption rate, correcting for carbon monoxide. This ranged from about 0.5 to 2 kW or roughly 10 to 30 kW/m², based on the approximate area visibly glowing.

The last type of smolder configuration referenced in Table 2-11.1 is quite pertinent to the scenario that makes smoldering a major contributor to residential fire deaths, i.e., upholstery and bedding fires initiated by cigarettes. This is frequently a composite problem, with the smoldering tendency of both the fabric and the substrate (polyurethane foam, cotton batting) pertinent to the overall smolder behavior of the combined assembly.²⁸ Ortiz-Molina *et al* have shown that the combination of a cellulosic fabric plus a polyurethane foam can smolder over a substantially wider range of conditions than can the foam alone.²⁹ The fabric smolder process supplies added heat to the foam smolder zone while simultaneously competing for oxygen. The full complexity of this interaction is yet to be explored. A considerable amount of empirical data on the tendency of cigarettes to initiate this type of smolder is available.³⁰⁻³⁶

The life hazard posed by smoldering bedding or upholstery within a closed room has been studied to some extent.³⁷⁻³⁹ Data have been presented³⁸ on the buildup of carbon monoxide (near the ceiling) in a 2.4 m room on a side due to cigarette-initiated smolder in a cotton mattress. The smolder front was reported to spread radially at a rate of 6.3×10^{-5} m/s independent of the size of the smoldering area. In two out of five tests the smolder process underwent a transition to flaming combustion after 65 to 80 minutes, which is close to the time at which total carbon monoxide exposure was estimated to be lethal. Similar data are reported³⁸ for a greater variety of bedding and upholstery materials; these were ignited by cigarettes (and by flaming sources) in a room $4.3 \times 3.6 \times 2.4$ m. Carbon monoxide and several other gases were sampled at three locations. Flaming developed from smoldering in several of the tests; this usually required 2 to 3 hours of smoldering first. Again, the total exposure to carbon monoxide from the smolder smoke approached or exceeded lethal levels. Lethal conditions due to carbon monoxide were reached in much shorter times in some cases.

All available data on the hazards of smoldering in a closed room were evaluated;³⁹ it was concluded that the probability of a lethal carbon monoxide dose and of transition to flaming are comparable for a period from 1 to 2½ hours after cigarette initiation of smoldering. A model is presented for buildup of carbon monoxide due to a smoldering fire;³⁹ the results generally show reasonable agreement

with experiment though some of the input parameters must be forced slightly.

In contrast to the above result, a more recent study of the fire risks associated with upholstered furniture implied that the toxic exposure from a smoldering chair in an "average" house was rarely fatal; transition to flaming brought with it death due to thermal causes.⁴⁰ The methodology was indirect; it involved using the Hazard I smoke movement and tenability models in a reasonably successful effort to reproduce national fire statistics for upholstery fires. There are not as yet sufficient data on the toxicity hazards of smoldering upholstery materials to definitively resolve this issue.

Transition to Flaming

The transition process from smolder to flaming in the above bedding and upholstery fires is essentially spontaneous. At room conditions both smoldering and flaming are possible in many such systems. Sato and Segal⁴¹ explored the domain of overlapping smolder and flaming potential for cellulosic materials and noted a hysteresis in the spontaneous transition between these two combustion modes. The mechanism of such a spontaneous transition has not been investigated in detail. It has been suggested on the basis of small mock-up studies that a chimneylike effect develops in the crevice between the horizontal and vertical cushions of a smoldering chair;⁴² the enhanced air supply presumably accelerates local char oxidation, heating the char to the point where it can ignite pyrolysis gases. Such a mechanism is plausible but it has not been demonstrated to be operable in real upholstery or bedding, where the chimney effect may not develop so readily.

Transition to flaming (fast exothermic gas-phase reactions) requires both a mixture of gases and air that are within their flammability limits and a sufficient heat source to ignite this mixture. Furthermore, these two requirements must be realized at the same locus in space and at the same time. Any factor that either enhances the net rate of heat generation or decreases the net rate of heat loss will move the smoldering material toward flaming ignition by increasing both local temperature and rate of pyrolysis gas generation. Such factors include an enhanced oxygen supply, an increase in scale (which usually implies lesser surface heat losses per unit volume of smoldering material), or an increasingly "concave" smolder front geometry, which reduces radiative losses to the surroundings and enhances gaseous fuel concentration buildup. All of these factors may be operating simultaneously in the case of upholstery and bedding smolder; sequential photos of smolder initiation, growth, and transition to flaming in an upholstered chair appear consistent with this idea.⁴²

A further factor in this and in other systems involving cellulosic materials is secondary char oxidation. This process is quite similar to the afterglow seen in cellulosic chars left by flaming combustion. Intense, high-temperature (probably greater than 1070 K) reaction fronts propagate intermittently in seemingly random directions through the fibrous low-density char left by the main lower temperature smolder front. In charred fabrics, these glowing fronts can sometimes progress in a stable manner along the charred residue of a single fiber, despite very high heat losses per unit volume of fuel. Such a process requires the catalytic action of alkali metals that are frequently found naturally in cellulose or left there during manufacture.^{43,44} While in a very hot smolder front the size of a single fiber is unlikely to

be sufficiently energetic to ignite flammable gases, the larger fronts (10^{-3} to 10^{-2} m in scale) may well be. An analogous process has been found to cause occasional flaming ignition of smoldering, unretarded cellulosic insulation.¹⁵

The transition from smolder to flaming can also be induced, for example, by a forced increase in oxygen supply rate to the smolder reaction zone.^{5,9,41,45,46} This was first studied quantitatively by Palmer⁵ for airflow over horizontal layers of wood sawdust; this process, of course, is familiar to anyone who has started a camp fire from tinder and sparks. Transition to flaming was noted by Palmer only for airflow in the same direction as smolder propagation (forward smolder); depending on the material, the transition occurred at airflow velocities from about 0.9 to 1.7 m/s. For these materials, flaming did not develop when the mean particle size was less than 1 mm. Ohlemiller⁴⁵ did obtain transition to flaming in layers of fibrous insulation materials of very small diameter (~ 25 μm) but again only with forward smolder; this occurred at air velocities of about 2 m/s for unretarded insulation. Leisch⁴⁶ utilized ignition sources placed midway along the length of grain and wood particle fuel layers so that forward and reverse smolder zones were simultaneously obtained; flaming was noted at 4 m/s air velocity only after the smoldering process produced a substantial depression or cavity in the surface of the fuel layer.

Ohlemiller⁴⁵ explained the weak response and lack of flaming transition in reverse smolder on the basis of heat transfer effects influencing the leading edge of the smolder reaction zone. These heat transfer effects intensify the smolder in the leading edge region for forward smolder. In the case of cellulosic insulation, the intensification leads to random development of small (a few cm) cavities near the leading edge which act as flame initiation regions and flame holders.

Ohlemiller⁴⁵ also found that both boric acid (a smolder retardant) and borax (a flame retardant) could each eliminate the transition to flaming when the retarded cellulosic insulation was the only fuel. However, the effectiveness of the acid and borax was substantially reduced if the smoldering fuel abutted unretarded wood; heat transferred from the smolder zone readily ignited the wood. Palmer⁴⁷ noted similarly that layers of fine dust that would not themselves undergo transition to flaming readily ignited adjacent flammable materials.

Smoldering solid wood undergoes a transition to flaming readily in a configuration that minimizes heat losses.^{26,27} It was inferred that the limiting variable in the transition is the surface temperature of the smoldering wood, with the transition occurring when that temperature reached about 950 to 1000 K.

CONCLUSION

Smoldering is a branch of solid fuel combustion quite distinct in many aspects from flaming, but equally diverse and complex. Unfortunately it has not been studied nearly to the same extent as flaming. This is quite apparent in the lack of quantitative guidelines that can be provided here for estimating the behavior of realistic smolder propagation processes, smolder detection, toxic gas production, and the transition to flaming. The experimental data provided can be readily used for closely analogous situations; they must be used cautiously for dissimilar conditions. The reader should always bear in mind the strong role that the oxygen supply

rate has on the smolder process. The other very important factor is the relative direction of movement of oxygen supply and smolder propagation; this can be somewhat obscure in many realistic configurations. The actual chemical nature of the fuel is relatively secondary, at least with regard to smolder rate. It may be important for toxic gas production rates, but the data here are quite limited.

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